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***Abstract* — A compact implantable printed meandered folded dipole antenna with a volume of 101.8 mm^3 and robust performance is presented for operation in the 2.4 GHz medical ISM bands. The implant antenna is shown to maintain its return loss performance in the 2360 – 2400 MHz, 2400 – 2483.5 MHz and 2483.5 – 2500 MHz frequency bands, simulated in eleven different body tissue types with a broad range of electrical properties. Bandwidth and resonant frequency changes are reported for the same antenna implanted in high water content tissues such as muscle and skin as well as low water content tissues such as subcutaneous fat and bone. The antenna was also shown to maintain its return loss performance as it was moved towards a tissue boundary within a simulated phantom testbed.**

***Index Terms*— Medical body area network; implantable medical devices; implanted antenna; body phantom;**

I. INTRODUCTION

Interest in Implantable Medical Devices (IMDs) has continued to rise, especially with the deployment of the Medical Body Area Network (MBAN) devices in the 2360 – 2400 MHz band, licensed by the Federal Communications Commission (FCC) [1] and the 2483.5–2500 MHz band by the European Telecommunications Standards Institute (ETSI) [2] in 2012. This is primarily due to the potential impact that IMDs could have on clinical applications, for example, the ability to obtain real-time biotelemetric data on a patient to enhance their diagnosis and treatment [3].

In the past, bulky, near field magnetic induction based technologies were the dominant method for communication between an in-body IMD and an external receiver [4]. A need for higher data rates and longer communication distances seen the introduction of the Medical Implant Communication Service (MICS) band (402 – 405 MHz) in 1999. Narrowband radio became the dominant method for IMD communication with many implant antennas designed to work within this band [5].

Reducing the overall volume of the implant device is one of the primary design goals for clinical applications. Many in-body implants are now battery powered as it increases functionality, therefore, having a more efficient wireless system gives the possibility of reduced battery volume or longer implant life with conservative power management. Compact and efficient implant antenna design is one of the most challenging issues for implants. One solution to reduce antenna size is to increase the operating frequency of the system. However, propagation losses in biological tissues increase with frequency, which reduces the overall efficiency of the system. Some losses can be countered by the gains in the efficiency of compact antennas as their electrical size increases [6]. This approach has been adopted and several implant antennas have been designed which operate in the 2400 – 2483.5 MHz Industrial Scientific Medical (ISM) band [7].

It is understood that an implant antenna's performance is strongly affected by the type of tissue that surrounds it [8] with potential radiation pattern distortion, reduced radiation efficiency and changes in antenna input impedance [9]. However, how much the antenna is affected is heavily dependent on the nature of the tissue in close proximity to the antenna and an ideal antenna would maintain its performance in the presence of all expected tissue types.

Tissue types can be classified into two main groups. The first are low water content tissue, which have relatively low permittivity and low conductivity such as bone and fats. The second are high water content tissue, which have higher permittivity and conductivity such as muscle and skin [10]. As the conductivity of the tissue around a given antenna changes, so too will the bandwidth, radiation pattern and radiation efficiency. Likewise, as the permittivity of the surrounding tissue changes, the wavelength within that tissue type changes, resulting in a resonant frequency shift of the implanted antenna [8].

While having relatively high dielectric material surrounding the antenna is advantageous when physically small antennas are required, this property cannot always be exploited successfully for in-body antennas, but instead can be a huge disadvantage. The human body is made up of a number of different tissues with different dielectric properties. The distribution, amount and exact dielectric properties of these tissues vary from person to person. An antenna designed for one tissue in one subject may not be suitable for another tissue or subject [5].

Previous work investigated the detuning effects on a MICS band antenna at different locations within the body and found a maximum detuning of 49 MHz and impedance mismatch difference of 22.6 dB from a reference performance in mean body tissue [11]. For an antenna to perform sufficiently at any location within the body, its performance must be robust enough to withstand any resonant frequency or bandwidth change that its current location may present. Therefore we present a compact, implantable antenna that sufficiently maintains its performance when implanted inside a broad range of different tissues or when placed close to tissue boundaries. The target operating bands are 2360 – 2400 MHz (US), 2400 – 2483.5 MHz (worldwide) and 2483.5 – 2500 MHz (EU). Section II details the antenna and the numerical test procedure used to evaluate its performance. Section III examines the results from the tests and the report concludes with a summary of the findings and suggestions for further work.

II. ANTENNA & TEST SETUP

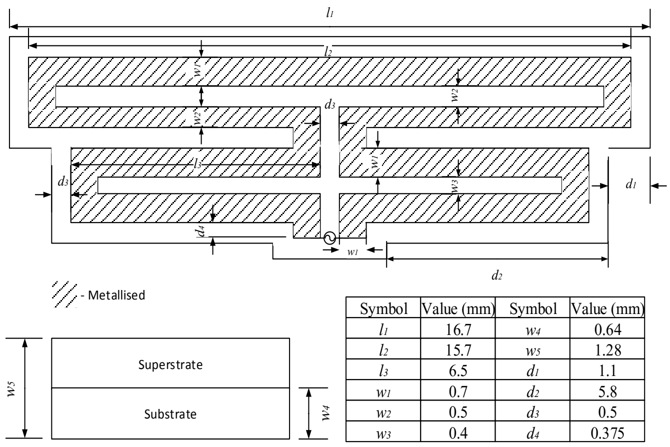
Typical implant tissue types listed in Table 1 were used within a numerical test bed. It is intuitive to expect that there will be a contrast in antenna performance between the high permittivity tissues such as muscle, stomach and skin in comparison to tissues with lower permittivity such as bone and Subcutaneous Adipose Tissue (SAT). In terms of propagation, the most problematic tissues are those with high conductivity and permittivity as the field attenuation is greatest.

Tissue Type	**Relative Permittivity**	**Conductivity (S/m)**
Stomach	62.3	2.15
Small Intestine	54.6	3.12
Kidney	52.9	2.37
Muscle	52.8	1.69
Brain	44.9	2.06
Liver	43.2	1.64
Skin	38.1	1.43
Lung (Inflated)	20.5	0.785
Bladder	18	0.668
Bone	11.4	0.381
SAT	10.8	0.259

TABLE 1 – DIELECTRIC PROPERTIES OF CHOSEN TISSUES AT 2.38 GHz [12]

To overcome the challenges associated with variable tissue properties, the antenna is required to have a wide impedance bandwidth to maintain an in-band return loss of -10 dB (VSWR =2) despite the resonant frequency shifts caused by the changing relative permittivity of the surrounding tissues. However, this is further compounded as tissue conductivity also decreases with permittivity between high and low water content tissues, changing the bandwidth of the antenna.

Another solution would be to design an antenna which has multiple resonances which would resonate as the antenna moves between different tissue types, maintaining the in-band return loss target value of -10 dB.



Symbol	Value (mm)	Symbol	Value (mm)
l_1	16.7	w_4	0.64
l_2	15.7	w_5	1.28
l_3	6.5	d_1	1.1
w_1	0.7	d_2	5.8
w_2	0.5	d_3	0.5
w_3	0.4	d_4	0.375

Figure 1- Antenna Geometry

The proposed antenna (Figure 1) is 16.7mm x 5.375mm with a volume of 101.833mm^3, making it suitable for implantation [8] with comparable size to the antennas reviewed in [13]. Rogers RT/duroid 6010 (ε_r = 10.8, σ = 0.0014), suitable for prototyping, was used as the substrate and superstrate materials and the antenna is coaxial probe fed. In the case of an antenna embedded within lossy media, the near field couples strongly with the surrounding material, thereby decreasing radiation efficiency [14]. To reduce this effect, a high permittivity substrate and superstrate are used to concentrate as much of the near field as possible within the low loss dielectric, rather than the lossy surrounding tissue. Although this material is not biocompatible, it does have similar dielectric properties to the biocompatible ceramic alumina 99.5% (ε_r = 9.8, σ = 1.0904e-7).

The Finite Difference Time Domain (FDTD) software Sim4Life by Zurich MedTech was used to simulate the antenna performance in various tissue types. The antenna model was placed in the centre of a 110mm x 110mm x 110mm cube. The size of the cube was optimized so that the return loss performance was not influenced by its proximity to the media boundary for all tissue types. The model used can be seen below in Figure 2.

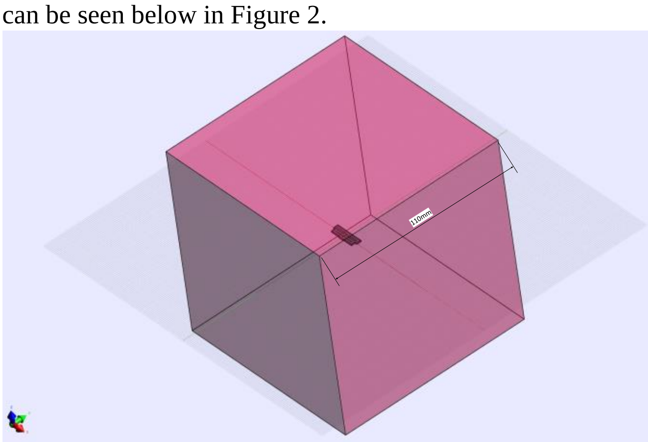


Figure 2 - Simulated Antenna Tissue Testbed

A second test for robust antenna performance is to investigate how the performance varies in proximity to boundaries between different tissue types. To do this, a second numerical phantom model was generated, replicating the shape of a layered human tissue phantom developed at Queen's University Belfast [15] [16]. The nylon shell was replaced with SAT and skin layers, each with a thickness of 2 mm, making a more realistic implant boundary condition. The inner core layer was filled with a muscle liquid, as in the original work. The antenna model was placed in the centre of the phantom and moved in ten 5 mm steps until the front surface of the superstrate came into contact with the SAT layer. S_{11} and radiation efficiency was observed for each step.

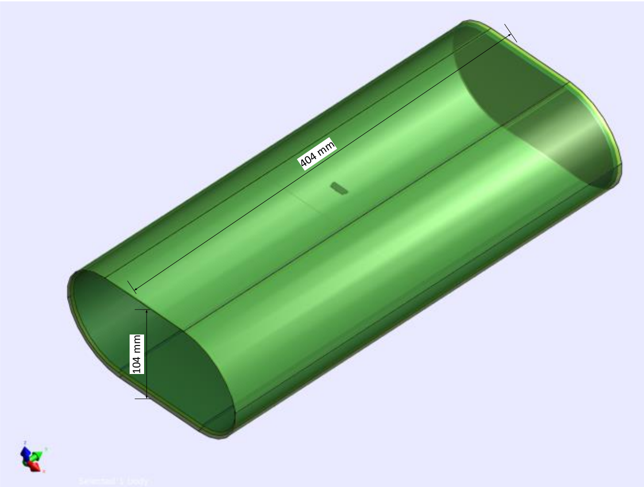
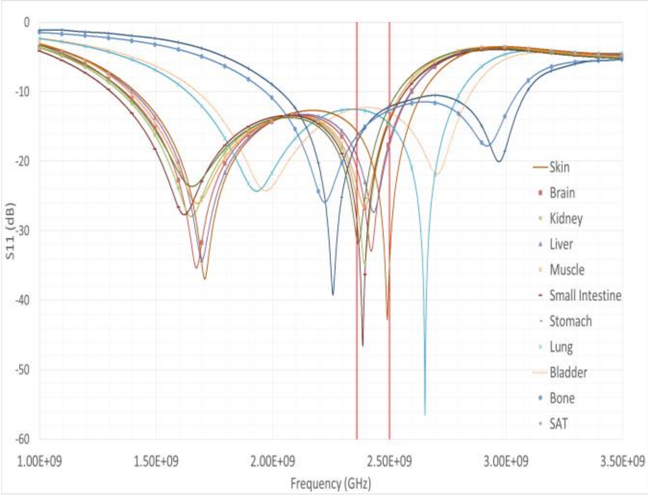


Figure 3 - Layered Phantom Testbed Model [15]

III. Results and Analysis

Return loss and radiation efficiency are used as the primary metrics for evaluating relative antenna performance in each tissue type. Radiation efficiency is a common metric for implant performance. However, it is related to the volume and shape of the media, as well as the position of the antenna relative to a boundary. Nonetheless, the Total Radiation Efficiency (TRE) results can be used to compare the relative performance of the same antenna in different tissues, when the aforementioned factors are constant. The reflection coefficient and TRE for each tissue type is shown in Table 2.

The results in Figure 4 and Table 2 show that the antenna maintains a return loss below -10 dB for the target frequency bands (frequency limits are highlighted by vertical lines in the figure) in all tissue types. As expected, the antenna had the highest resonant frequencies at 2.257 and 2.968 GHz when embedded in SAT tissue, due to its relatively low permittivity. The antenna had the lowest resonant frequency in small intestine tissue despite this tissue not having the highest permittivity of the tissue types tested. This is due to small intestine tissue having the highest conductivity of the tissues tested, giving the antenna the largest bandwidth when embedded in it.



Tissue Type	Resonant Frequency (GHz)	Return Loss (dB)	-10 dB Bandwidth (GHz)	TRE @ 2.38 GHz (%)	Peak Spatial Average SAR (W/kg)*
Stomach	1.655, 2.368	-23.64, -31.79	1.358 - 2.536 (49.5%)	0.0054	0.32
Small Intestine	1.625, 2.385	-27.68, -46.38	1.306 - 2.567 (52%)	0.00025	0.419
Kidney	1.649, 2.394	-27.94, -34.8	1.345 - 2.566 (51.3%)	0.0019	0.359
Muscle	1.676, 2.394	-26.06, -26.64	1.386 - 2.556 (49.2%)	0.015	0.289
Brain	1.672, 2.421	-35.35, -32.91	1.364 - 2.592 (51.5%)	0.0032	0.351
Liver	1.697, 2.432	-34.18, -27.35	1.399 - 2.595 (50.2%)	0.011	0.305
Skin	1.706, 2.492	-36.86, -42.68	1.411 - 2.646 (51.8%)	0.017	0.289
Lung (Inflated)	1.932, 2.65	-24.31, -56.51	1.634 - 2.805 (49.2%)	0.097	0.401
Bladder	1.969, 2.699	-24.27, -21.84	1.676 – 2.852 (49.4%)	0.16	0.254
Bone	2.217, 2.913	-25.84, -17.77	1.968 - 3.054 (45.6%)	1.04	0.174
SAT	2.257, 2.968	-39.21, -20.06	2.033 - 3.089 (44.4%)	2.81	0.193

Figure 4 - Graph of S11 vs Tissue Type

*For 1mW input power over 1g tissue cubes

Table 2- Simulated Results For Antenna Placed in Centre of Various Tissue Cubes

The TRE of the antenna decreased as the conductivity of the tissue in increased. The antenna was most efficient when embedded in SAT and least efficient when embedded in small intestine tissue. The only exception to this was between skin and liver tissue, with the antenna being more efficient in skin despite it having a higher conductivity. This can be attributed to the antenna having a higher mismatch efficiency in skin despite having a slightly lower radiation efficiency when compared to liver, therefore producing a higher TRE.

Specific Absorption Rate (SAR) is an important factor to take into consideration when designing implant antennas as patient safety is of the utmost importance. Peak spatial average SAR (psSAR) was calculated over 1g of tissue for each tissue type according to the IEEE/IEC62704-1 standard with an input power of 1mW. As can be seen from Table 2, the psSAR never exceeds the recommended safety limit of 1.6 W/kg for all tissue types.

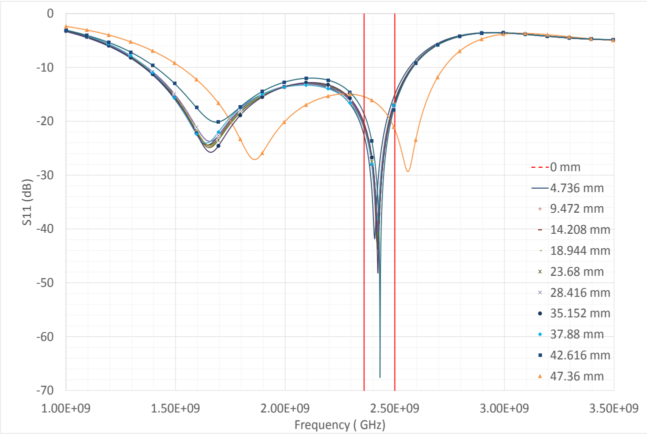


Figure 5 - Graph of S11 vs Displacement from Centre of Tissue Cube towards Tissue Boundary

The tissue boundary investigative results can be seen in Figure 5. S_{11} was not affected until the antenna came to within 5 mm from the boundary. The greatest change was encountered when the antenna was placed up against the SAT layer boundary, causing a slight frequency and bandwidth change as the antenna near field encountered the lower permittivities and conductivities of the other layers. Nonetheless, the antenna maintained a return loss below -10dB for all target frequency bands for all antenna positions investigated from the centre of the phantom to the boundary between the muscle and SAT layers.

IV. Conclusions and Future Work

A compact, implantable antenna for MBAN operation in the 2360 – 2400 MHz, 2400 – 2483.5 MHz and 2483.5 – 2500 MHz bands is presented. The antenna maintains a return loss below -10 dB in eleven different tissues with a broad range of electrical properties (permittivity and conductivity). The antenna was also shown to maintain S_{11} performance as the antenna moved from the centre of the numerical phantom testbed towards a tissue boundary. Further work will include prototyping and validating antenna performance using experimental measurements.

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